VI.11 Techno-Economic Feasibility of Highly-Efficient Cost-Effective Thermoelectric-SOFC Hybrid Power Generation Systems

Objectives

Phase I

- Create innovative integrated SOFC-Thermoelectric (TE) technical concepts meeting the requirements of 65% electric efficiency and $400/kWe.
- Develop techno-economic models to assess the feasibility of the created concepts using trade studies.

Phase II

- Propose development and risk-mitigation tasks for inserting the proposed technology into a coal-based power plant.

Accomplishments

- Generated 10 component and system technical concepts.
- Benchmarked the TE-material technologies, emphasizing power generation using SOFC exhaust heat.
- Developed system level performance and cost modeling tool.
- Identified a pressurized SOFC with TE power generation as the optimal system configuration.

Future Directions

- Complete the optimization in design and operating envelopes.

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- Evaluate the barriers and enablers in terms of technology and cost.
- Create Phase II development plan.

Introduction

A thermoelectric (TE) material can generate power directly when it is conducting heat from a hot fluid to a cold one, known as Seebeck Effect. In a solid oxide fuel cell (SOFC), the exhaust fluid leaving the stack and its afterburner typically has a high temperature of around 800ºC. In today's SOFC designs, the exhaust heat is usually recovered in a heat exchanger, or preheater, to preheat the fuel or air entering the stack. A TE generator can be used for the same heat recovery purpose and also for converting part of the heat to electricity directly. The additional electricity increases the system power generation efficiency, and has the potential to meet the SECA power efficiency goal of 65%.

The major issue in a SOFC-TE hybrid power generation system is the trade-off between the gain in efficiency and the associated cost. Major factors affecting system performance and cost include SOFC pressurization, exhaust heat temperature and flow rate, TE size, material cost, and TE power efficiency under exhaust heat conditions, among others such as blower efficiency. This study is concerned with the trade-off between the performance and cost in reaching the overall system performance and cost target.

Approach

The proposed approach is tailored to 10 kWe SOFC-TE modules with the prospect of studying the impact of capacity ranging from 5 kWe to 200 kWe power plants. In-depth system/component techno-economic models will be developed and verified for the proposed SOFC-TE integrated system. The models will be exercised to explore the design and operating techno-economic envelopes (trade-offs). Several existing TE-material technologies will be evaluated and benchmarked in support of the selection of strategic partner(s) for Phase II. Product requirements and specifications (system/components) will result from the techno-economic analysis. An evaluation of the critical barriers/enablers will lead to the creation of a development plan for Phase II.

Results

TE Material Benchmarking

A list of close to 30 TE materials studied or commercialized in America, Asia and Europe was reviewed varying from manufacturing processes to material structure. TE materials at high and medium temperature range were the focus for power generation from SOFC exhaust. TE materials with a thermoelectric figure of merit (ZT) around 1 at medium temperature levels have achieved fair commercialization with high technology readiness levels [1]. Higher ZTs of 3.2 have been achieved at Lincoln Lab [2] but, to our best knowledge, all reported TE materials with high ZTs today have technology readiness level below or equal to 4.

Concept Generation

Ten concepts were generated to integrate the two subsystems, SOFC and TE, considering the system efficiency and cost targets. Among these concepts, three are in terms of system configuration, for which the number of TE generators and the TE relative positions with respect to the SOFC components are proposed. Another three concepts are related to the design of new components or the performance and cost tradeoffs for certain components. The rest of the concepts are for power conditioning system integration.

The pros and cons of the above concepts were analyzed qualitatively from configuration and practicality standpoints. Trade studies using physics-based models were used for the analysis of the other remaining concepts.

System Modeling Analysis

Cost and physics-based models are used to compare the systems and to support the concept selection process.

One of the system concepts mentioned above has been identified as the best system to meet the 65% system electrical efficiency at a cost of $432/kWe assuming a ZT of 2 for the TE generator. It consists of one TE generator integrated in a pressurized SOFC system that has a stack pressure of approximately 4 atm and uses a separate air blower for the TE generator, as shown in Figure 1. The baseline (used for comparison) ambient pressure SOFC system in this study has an efficiency of 43% (based on lower heating value). Using two TE generators, the system efficiency can increase up to approximately 55%. To reach 65% system efficiency, a pressurized SOFC integrated with a Brayton cycle is necessary. In such a configuration, however, the TE module tends to generate less power than in an ambient pressure SOFC. The reasons for this are summarized hereafter. The exhaust gas from the SOFC afterburner first passes through a turbine and its temperature is lowered after the expansion process. In addition, the cooling air for the high-stage TE generator has a higher temperature due to compression than in an ambient SOFC. These combined effects reduce the amount of energy available for the TE generator and also reduce the temperature difference between the hot and cold fluids across the TE generator.

An alternative to increase the TE generator performance is to feed the ambient "cold" air first to the TE and then to the air compressor. However, the gain on the TE power generation is outweighed by the additional compression work to compress the "hot" air and results in lower system efficiency.

The system efficiency as a function of the system pressurization ratio is shown in Figure 2. System efficiency shows a peak around a pressure ratio of 4. At pressure ratio ~4, the TE generator contributes approximately 2 percentage points to the system efficiency of 63%. At higher pressure ratios, the drop in system efficiency is dominated by the turbine-compressor module. Additional investigation and system optimization is underway to reach 65% system efficiency.

The air preheater in Figure 1 can be used as another TE generator to produce additional power. However, as shown in Figure 3, as this TE generator size becomes larger, i.e., the number of parallel elements increases from 0 to 18,000, the system cost increases from $510/kW to $560/kW but the efficiency increases only ~1%. This TE generator therefore does not seem to be cost-effective. In addition, the heat transfer capability using TE materials is reduced compared to a metal heat recovery device. This means that a higher heat transfer area is required to achieve the same performance than a
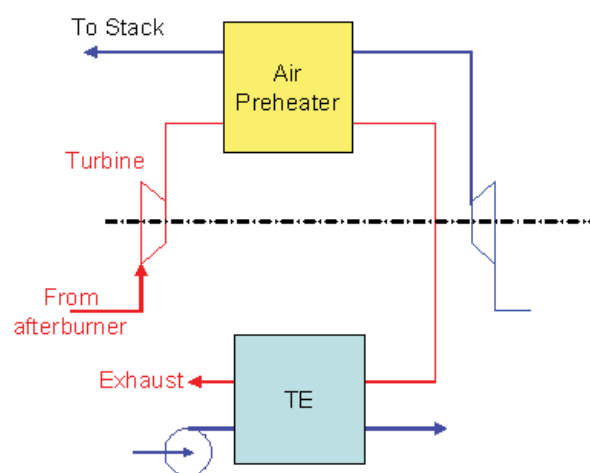

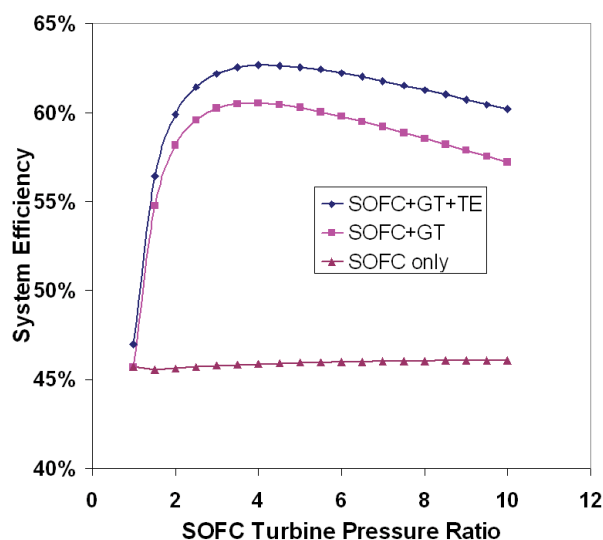**FIGURE 1.** TE Generator and SOFC Integration Scheme

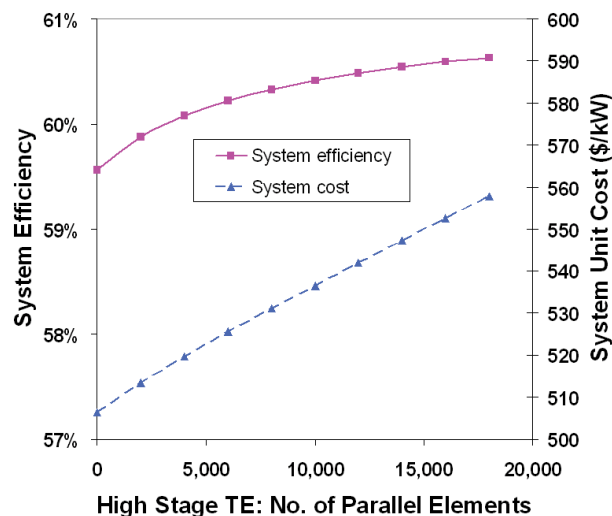**FIGURE 2.** System Efficiency at Different SOFC Pressure Ratios

FIGURE 3. Power Cost When Using Air Preheater as a TE Generator

FIGURE 4. System Efficiency with TE Materials Having Different ZTs

Conclusions

- The TE contribution to the system is small due to system thermodynamic constraints.
- The best system configuration is a pressurized SOFC with a bottoming TE power generation module.
- In the pressurized SOFC-TE systems, the TE power generator module contributes approximately 2% (absolute) of the system efficiency.
- The maximum system efficiency obtained to date is 63% and further system optimization is underway to meet the performance and cost targets.

References

1. Bottner, "Micropelt Miniaturized Thermoelectric Devices: Small Size, High Cooling Power Densities, Short Response Time", ICT 2005, Clemson, S.C.

2. Temperature Rises for Devices That Turn Heat Into Electricity, Robert F. Service, Science 29 October 2004 306: 806-807.

3. Bell, L. E., "Use of Thermal Isolation to Improve Thermoelectric System Operating Efficiency," Proceedings 21st International Conference on Thermoelectrics, Long Beach, CA, August 2002.

pressurized SOFC-TE with only one TE power generator module as depicted in Figure 1.

As the TE efficiency is a function of ZT, the system efficiency with different ZTs is modeled with a SOFC pressure ratio of 4, as shown in Figure 4. When the ZT changes from 1 to 3.5 [3], the TE generator efficiency increases from 0.06 to 0.14. Because TE power generation is only a small portion of the system power, the system efficiency incr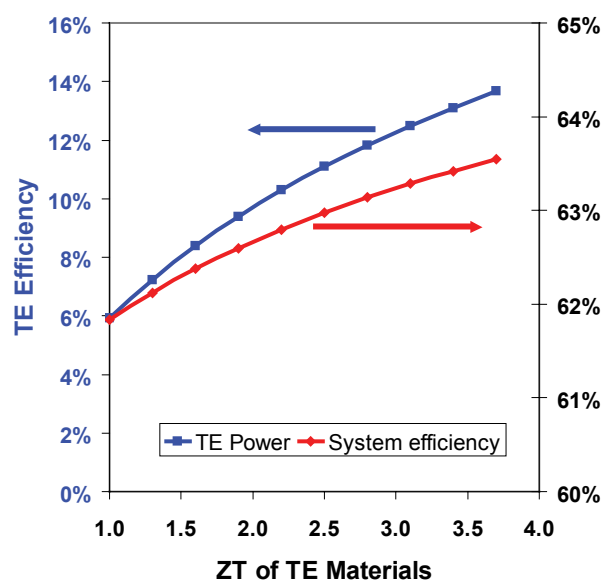eases by only less than 2 percentage points.